Pre-Processing of Galaxies before Entering a Cluster

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Abstract

We consider several mechanisms that possibly affect the evolution of disk galaxies in clusters using analytical models based on a hierarchical clustering scenario. We especially focus on the evolution of disk galaxies in subclusters located around a main cluster. We show that ram-pressure stripping cannot be always ignored in subclusters, although their masses are much smaller than that of the main cluster. The star-formation rate of a galaxy may gradually decrease by the stripping of warm gas ('strangulation') in a main cluster. However, we find that ram-pressure stripping could start before the strangulation is completed, if a field galaxy directly falls into the main cluster. Since this conflicts with some recent observations, many galaxies might have been affected by some environmental effects when they were in subclusters before they fell into the main cluster ('pre-processing'). We show that strangulation and evaporation of the cold gas by the surrounding hot ICM in subclusters are the possible candidates. We also show that the observed morphological transformation of disk galaxies at $z \lesssim 1$ is not chiefly due to galaxy mergers.

Key words: galaxies: clusters: general—galaxies: evolution—galaxies: high-redshift—galaxies: interactions

1. Introduction

Clusters of galaxies in the redshift range of $z \gtrsim 0.2$ often exhibit an overabundance, relative to present-day clusters, of blue galaxies (Butcher, Oemler 1978, 1984). This star-formation activity is often called the Butcher–Oemler effect, and subsequent studies have confirmed this trend (Couch, Sharples 1987; Rakos, Schombert 1995; Lubin 1996; Margoniner, de Carvalho 2000; Ellingson et al. 2001; Goto et al. 2003a). At the same time, various studies have reported a morphological evolution in cluster galaxies; they have shown that the fractions of S0 galaxies in clusters decrease toward a higher redshift (Dressler et al. 1997; Couch et

al. 1994, 1998; Fasano et al. 2000). For many clusters, it has been found that their galaxy population gradually changes from a red, evolved, early type population in the inner part of the clusters to a progressively blue, later type population in the extensive outer envelope of the clusters (Abraham et al. 1996; Balogh et al. 1997; Rakos et al. 1997; Oemler et al. 1997; Smail et al. 1998; Couch et al. 1998; van Dokkum et al. 1998). These are often interpreted as being the result that star-forming field disk galaxies infalling to a cluster are transformed to passively evolving cluster members.

Various mechanisms have been proposed for the transformation. In general, galaxies in the inner region of a cluster have lower star-formation rates both at $z \sim 0$ (Lewis et al. 2002; Gavazzi et al. 2002; Graham et al. 2003) and at higher redshift (Couch, Sharples 1987; Balogh et al. 1997, 1999b; Poggianti et al. 1999; Postman et al. 2001; Couch et al. 2001; Balogh et al. 2002c). Ram-pressure stripping of cold gas in the disk of a galaxy is a possible candidate for the suppression of star formation in clusters because the removal of cold gas leads to the exhaustion of an ingredient of stars (Gunn, Gott 1972; Balsara et al. 1994; Fujita, Nagashima 1999; Abadi et al. 1999; Quilis et al. 2000; Mori, Burkert 2000; Vollmer et al. 2001; Bicker et al. 2002), although ram-pressure may cause a mild increase of star formation of a galaxy (Fujita, Nagashima 1999) or a starburst with a short-time scale (Bekki, Couch 2003; Gavazzi et al. 2003). Ram-pressure stripping is likely to take place in the central regions of clusters because the density of intracluster medium (ICM) is high there. In fact, disk galaxies with a deficit of cold gas or a morphological sign of gas removal are often observed near cluster centers (Cayatte et al. 1990; Vollmer et al. 2000; Bravo-Alfaro et al. 2000, 2001; Solanes et al. 2001; Bureau, Carignan 2002; Vollmer 2003; Sofue et al. 2003; Yoshida et al. 2003). Moreover, it is more effective in richer clusters because the typical velocity of galaxies is larger. Several authors actually indicated that the fractions of blue galaxies are systematically lower for rich clusters than for poor clusters at a given redshift (Margoniner et al. 2001; Goto et al. 2003a), which is consistent with a suppression of the star-formation activities by ram-pressure stripping. On the other hand, Balogh et al. (2002b) investigated clusters with small masses at $z \sim 0.25$, and indicated that the striking similarity between the spectral and morphological properties of galaxies in these clusters and those of galaxies in more massive systems at similar redshifts implies that the physical processes responsible for truncating star formation in galaxies are not restricted to the rare, rich cluster environment, but are viable in much more common environments. Thus, they concluded that ram-pressure stripping cannot be solely responsible for the low star-formation rates in these systems. Moreover, several authors indicated that ram-pressure stripping cannot account for the suppression of star formation observed $\sim$Mpc away from the center of a cluster (Balogh et al. 1997; Kodama et al. 2001; Lewis et al. 2002), although we will show that it is not obvious.

Larson et al. (1980) suggested that an infall from gaseous galactic halos might be important for sustaining star formation in spiral galaxies and that the gas in these halos might be

stripped in the cluster environment, leading to the formation of passively evolving S0 galaxies. Although the gas in galactic halos, which we call 'warm gas', has not been detected in nearby spiral galaxies (Benson et al. 2000), models of galaxy formation based on the hierarchical clustering scenario have often assumed such an infall, and have been very successful in accounting for the properties of galaxies at optical and infrared wavelengths (Cole et al. 1994; Baugh et al. 1996; Kauffmann et al. 1999; Nagashima, Gouda 2001). If only warm gas is stripped, star formation may be allowed to continue by consuming the remaining cold disk gas, but without the infall to replenish this supply, star formation will die out on timescales of a few Gyr (Larson et al. 1980). This is consistent with observations that indicate a slow decline of the star-formation rates of galaxies (Balogh et al. 1999b; Kodama, Bower 2001). We call this scenario 'strangulation' from now on. In this paper, we also consider the evaporation of cold gas in disk galaxies by energy transfer via thermal conduction from the surrounding hot ICM as another mechanism for the slow decline of the star-formation rates. As far as we know, this is the first time that the redshift evolution of the evaporation effect has been studied.

The above mechanisms, that is, ram-pressure stripping, strangulation, and evaporation, mainly have an influence on the star-formation activities of galaxies. Contrary to them, galaxy mergers are expected to significantly affect the morphology of galaxies. Thus, mergers may have played an important role in the observed morphological transformation in clusters. Mergers between galaxies with comparable masses (major mergers) could create elliptical galaxies (Toomre, Toomre 1972). However, major mergers alone cannot account for the observed fractions of galaxies with intermediate bulge-to-disk luminosity ratios such as S0 galaxies in clusters (Okamoto, Nagashima 2001; Diaferio et al. 2001). Okamoto and Nagashima (2003) indicated that mergers between galaxies with significantly different masses (minor mergers) may produce the galaxies with intermediate bulge-to-disk luminosity ratios because these mergers do not disrupt galactic disks completely.

In this paper, we consider possible mechanisms responsible for the truncation of star formation and morphological transformation of disk galaxies in clusters. In particular, we investigate the evolution of disk galaxies in subclusters. Recent observations show that galaxies have already been affected by some environmental effects in subclusters (Kodama et al. 2001; Treu et al. 2003; Goto et al. 2003b). We define subclusters as clusters located around a larger cluster (main cluster) at relatively high redshift; these subclusters are to be merged with the main cluster until $z=0$. Thus, at high redshift, we can say that these subclusters are progenitors of the main cluster at $z=0$. On the other hand, at low redshift, they become subhalos included in the main cluster. Since high-resolution N-body simulations showed that a subcluster that has been included in the main cluster as a subhalo is not completely destroyed (Moore et al. 1999; Okamoto, Habe 1999; Ghigna et al. 2000; Fukushige, Makino 2001), we do not explicitly discriminate a subcluster from a subhalo. However, we can estimate the time when subclusters are included by the main cluster (see section 3).

We consider the effect of cosmological evolution of clusters since the inner structure of clusters at high redshift is not the same as that at low redshifts, which makes differences of environmental effects on cluster galaxies at between high and low redshift. We take an analytical approach to study the environmental effects because at the moment it is difficult to study their redshift evolutions by genuine numerical simulations. For example, it is virtually impossible to study ram-pressure stripping of galaxies in clusters by cosmological numerical simulations including both dark matter and gas with a resolution that is sufficient to treat the interaction between ICM and interstellar gas in each galaxy correctly. Even if we introduce some assumptions about the stripping of the interstellar gas and the distribution of the ICM, as is done by Okamoto and Nagashima (2003), we need to find the average cluster and galaxy evolutions at least in terms of their dark halos. However, it is time-consuming to create many clusters by performing high-resolution N-body simulations to follow the average cluster and galaxy evolutions. Moreover, there is another merit for analytical approaches. Even in the future, when full numerical simulations are enabled, the simulations must include many physical processes, and it would be difficult to divide them when the results are analyzed. The division is easier for analytical studies, and the results of analytical studies would be very useful to be compared with those of numerical simulations. We also emphasize that our model is different from previous semi-analytic models. Our model takes account of spatial correlations among initial density fluctuations, and can specifically predict the evolution of subclusters around the main cluster. On the other hand, previous models cannot discriminate between subclusters and the main cluster.

We mainly consider massive disk galaxies since they can be observed in detail even at high redshift. Thus, we do not consider the cumulative effect of high-speed encounters between galaxies ('galaxy harassment') because it influences disk galaxies with small masses (Moore et al. 1996). We mostly study the redshift evolution of each environmental effect and discuss the relative strength of the effect at high and low redshift. We also compare results with observations qualitatively.

This paper is organized as follows. In section 2, we summarize our models. In section 3 we give the results of our calculations, and compare them with observations in section 4. Summary and conclusions are given in section 5. Readers who are interested only in the results of calculations may skip section 2.

2. Models

2.1. The Growth of Clusters

In this study, the average mass of progenitors of a cluster is derived from the extend Press–Schechter model (EPS) (Bower 1991; Bond et al. 1991; Lacey, Cole 1993) and its further extention (Fujita et al. 2002). The latter is a Press–Schechter model including the effect of

spatial correlations among initial density fluctuations (SPS). We briefly explain the model here; the details are shown in Fujita et al. (2002).

We can estimate the conditional probability, $P(r, M_1, M_2)$, of finding a region of mass M_1 with $\delta_1 \geq \delta_{\rm c1}$ at a distance r from the center of an isolated, finite-sized object of mass M_2, provided that the object of mass M_1 is included in the object of mass M_2 ($> M_1$) with $\delta_2 = \delta_{\rm c2}$ at $r = 0$. Here, we define δ_M as the smoothed linear density fluctuation of mass scale M, and $\delta_1 = \delta_{M_1}$ and $\delta_2 = \delta_{M_2}$. Moreover, we define $\delta_{\rm c}(z)$ as the critical density threshold for a spherical perturbation to collapse by the redshift z, and $\delta_{\rm c1} = \delta_{\rm c}(z_1)$ and $\delta_{\rm c2} = \delta_{\rm c}(z_2)$. In the Einstein–de Sitter universe, $\delta_{\rm c}(z) = 1.69(1+z)$.

The probability can be written as

$$P(r, M_1, M_2) = \frac{1}{\sqrt{2\pi[1-\epsilon^2(r)]}} \int_{\nu_{1\rm c}}^{\infty} \exp\left\{ \frac{-[\nu_1 - \epsilon(r)\nu_{2\rm c}]^2}{2[1-\epsilon^2(r)]} \right\} d\nu_1 \,, \tag{1}$$

where ν_1 and ν_2 are defined by

$$\nu_1 \equiv \frac{\delta_1}{\sigma_1}\,,\, \nu_2 \equiv \frac{\delta_2}{\sigma_2}\,,\, \sigma_1 \equiv \sigma(M_1)\,,\, \sigma_2 \equiv \sigma(M_2)\,,\, \nu_{1\rm c} \equiv \frac{\delta_{\rm c1}}{\sigma_1}\,,\, \nu_{2\rm c} \equiv \frac{\delta_{\rm c2}}{\sigma_2}\,, \tag{2}$$

respectively (Yano et al. 1996). In equation (1), $\epsilon(r)$ is defined by

$$\epsilon(r) \equiv \frac{\sigma_{\rm c}^2(r)}{\sigma_1 \sigma_2}\,, \tag{3}$$

where $\sigma_{\rm c}^2(r)$ is the two-point correlation function. In equation (2), $\sigma(M)$ is the rms density fluctuation smoothed over a region of mass M.

We can rewrite equation (1) as

$$P(r, M_1, M_2) = \frac{1}{\sqrt{2\pi}} \int_{\beta}^{\infty} e^{-y^2/2} dy \,, \tag{4}$$

where

$$\beta(r) = \frac{\nu_{1\rm c} - \epsilon(r)\nu_{2\rm c}}{\sqrt{1-\epsilon^2(r)}} = \frac{1}{\sqrt{1-\epsilon^2(0)\alpha^2(r)}} \frac{\delta_{\rm c1}}{\sigma_1} \left[1 - \frac{\delta_{\rm c2}}{\delta_{\rm c1}} \alpha(r) \right] , \tag{5}$$

and $\alpha(r) = \epsilon(r)/\epsilon(0)$. The spatially averaged conditional probability for $R_{\rm in} < r < R_{\rm out}$ in a precluster region is defined as

$$P(M_1, M_2) = \int_{R_{\rm in}}^{R_{\rm out}} P(r, M_1, M_2) 4\pi r^2 dr \Big/ \int_{R_{\rm in}}^{R_{\rm out}} 4\pi r^2 dr \,. \tag{6}$$

The conditional probability that a particle which resides in a object ('halo') of mass M_2 at redshift z_2 is contained in a smaller halo of mass $M_1 \sim M_1 + dM_1$ at redshift z_1 ($z_1 > z_2$) is

$$P_{\rm SPS}(M_1, t_1 | M_2, t_2) dM_1 = 2 \left| \frac{\partial P(M, M_2)}{\partial M} \right|_{M=M_1} dM_1 \,, \tag{7}$$

where the factor of two is based on the usual Press–Schechter assumptions.

If we fix $r = 0$ in equation (4), we can obtain the conditional probability that a particle which resides in a object of mass M_2 at redshift z_2 is contained in a smaller halo of mass $M_1 \sim M_1 + dM_1$ at redshift z_1 ($z_1 > z_2$) in the sense of EPS:

$$P_{\rm EPS}(M_1,z_1|M_2,z_2)dM_1 = 2\left|\frac{\partial P(0,M,M_2)}{\partial M}\right|_{M=M_1} dM_1 \tag{8}$$

(Fujita et al. 2002). This means that the probability represented in the EPS model is that represented at the center of the halo M_2 in the SPS model [$R_{\rm out}\rightarrow 0$ in equation (7)].

We define the typical mass of halos at redshift z that become part of a larger halo of mass M_0 at a later time $z_0(< z)$ as

$$\bar{M}_{\rm SPS}(z|M_0,z_0) = \frac{\int_{M_{\rm min}}^{M_0} M P_{\rm SPS}(M,z|M_0,z_0)dM}{\int_{M_{\rm min}}^{M_0} P_{\rm SPS}(M,z|M_0,z_0)dM}\:, \tag{9}$$

where $M_{\rm min}$ is the lower cutoff mass. We choose $M_{\rm min}=10^8\,M_\odot$, which corresponds to the mass of dwarf galaxies. If $R_{\rm in}>0$, equation (9) shows the typical mass of progenitor halos, excluding the main halo at $r\approx 0$. At lower redshift, those progenitor halos should be included in the main halo, and would become subhalos in it. However, at higher redshift, they should reside around the main halo.

On the other hand, since $P_{\rm EPS}$ corresponds to $P_{\rm SPS}$ when $R_{\rm out}$ approaches zero, the average mass defined by

$$\bar{M}_{\rm EPS}(z|M_0,z_0) = \frac{\int_{M_{\rm min}}^{M_0} M P_{\rm EPS}(M,z|M_0,z_0)dM}{\int_{M_{\rm min}}^{M_0} P_{\rm EPS}(M,z|M_0,z_0)dM} \tag{10}$$

is the expected mass of the main halo that is expected to be at $r\sim 0$. In Fujita (2001a, hereafter Paper I), we used $\bar{M}_{\rm EPS}$ as the typical mass of progenitors of a cluster. However, the results should be regarded as those for the main cluster.

2.2. *Ram-Pressure Stripping*

We adopt the ram-pressure stripping model of Paper I. We summerize it briefly. In the following sections, we often refer to a relatively large dark halo containing galaxies and gas as a 'cluster' and do not discriminate it from a group or a subcluster.

2.2.1. *Distributions of dark matter and the ICM*

The virial radius of a cluster with virial mass $M_{\rm vir}$ is defined as

$$r_{\rm vir} = \left[\frac{3\,M_{\rm vir}}{4\pi\Delta_{\rm c}(z)\rho_{\rm crit}(z)}\right]^{1/3}\:, \tag{11}$$

where $\rho_{\rm crit}(z)$ is the critical density of the universe and $\Delta_{\rm c}(z)$ is the ratio of the average density of the cluster to the critical density at redshift z. The latter is given by

$$\Delta_{\rm c}(z) = 18\,\pi^2 + 82x - 39x^2\:, \tag{12}$$

for a flat universe with a non-zero cosmological constant (Bryan, Norman 1998). In equation (12), the parameter x is given by $x=\Omega(z)-1$. The average density of a cluster, $\rho_{\rm vir}(z)\equiv \rho_{\rm crit}(z)\Delta_{\rm c}(z)$, is an increasing function of z. In the Einstein–de Sitter Universe, for instance, $\rho_{\rm vir}(z)\propto(1+z)^3$.

We assume that a cluster is spherically symmetric and the density distribution of dark matter is

$$\rho_{\rm m}(r) = \rho_{\rm mv}(r/r_{\rm vir})^{-a}\,, \tag{13}$$

where $\rho_{\rm mv}$ and a are constants, and r is the distance from the cluster center. We choose $a = 2.4$, because the slope is consistent with observations (Horner et al. 1999). Moreover, the results of numerical simulations show that the mass distribution in the outer region of clusters is approximately given by equation (13) with $a \sim 2.4$ (Navarro et al. 1996, 1997). We adopt a power-law rather than the full NFW profile to avoid specifying a particular value for the concentration parameter and its variation with cluster mass and formation redshift. We ignore the self-gravity of ICM.

We consider two ICM mass distributions. One follows equation (13), except for the normalization and the core structure,

$$\rho_{\rm ICM}(r) = \rho_{\rm ICM,vir}\frac{[1+(r/r_{\rm c})^2]^{-a/2}}{[1+(r_{\rm vir}/r_{\rm c})^2]^{-a/2}}\,. \tag{14}$$

The ICM mass within the virial radius of a cluster is

$$M_{\rm ICM} = \int_0^{r_{\rm vir}} 4\pi r^2 \rho_{\rm ICM}(r) dr\,. \tag{15}$$

The normalization $\rho_{\rm ICM,vir}$ is determined by the relation $f_{\rm b} = M_{\rm ICM}/M_{\rm vir}$, where $f_{\rm b}$ is the gas or baryon fraction of the universe. This distribution corresponds to the case where the ICM is in pressure equilibrium with the gravity of the cluster and is not heated by anything other than the gravity. We introduce the core structure to avoid the divergence of gas density at $r = 0$ and use $r_{\rm c}/r_{\rm vir} = 0.1$. We call this distribution the 'non-heated ICM distribution'. We use $f_{\rm b} = 0.25(h/0.5)^{-3/2}$, where the present value of the Hubble constant is written as $H_0 = 100\,h\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

We also consider another ICM distribution when ICM is heated non-gravitationally before cluster formation. At least for nearby clusters and groups, observations suggest that such non-gravitational heating did happen (Ponman et al. 1999; Lloyd-Davies et al. 2000; Mulchaey 2000; Mulchaey et al. 2003). Although there is a debate about whether the heating took place before or after cluster formation (Fujita 2001b; Yamada, Fujita 2001), the following results would not be much different even if ICM is heated after cluster formation (Loewenstein 2000). Following Balogh et al. (1999a), we define the adiabat $K_0 = P/\rho_{\rm g}^\gamma$, where P is the gas pressure, $\rho_{\rm g}$ is its density, and $\gamma\,(= 5/3)$ is a constant. If ICM had already been heated before accreted by a cluster, the ICM fraction of the cluster is given by

$$f_{\rm ICM} = \min\left\{0.040\left(\frac{M_{\rm vir}}{10^{14}\,M_\odot}\right)\left(\frac{K_0}{K_{34}}\right)^{-3/2}\left[\frac{t(z)}{10^9\,{\rm yr}}\right],\, f_{\rm b}\right\}\,, \tag{16}$$

where $K_{34} = 10^{34}\,{\rm erg\,g^{-5/3}\,cm^2}$ (Balogh et al. 1999a).

The virial temperature of a cluster is given by

$$\frac{k_\mathrm{B}T_\mathrm{vir}}{\mu m_\mathrm{H}} = \frac{1}{2}\frac{GM_\mathrm{vir}}{r_\mathrm{vir}}\,, \tag{17}$$

where k_B is the Boltzmann constant, μ (= 0.61) is the mean molecular weight, m_H is the hydrogen mass, and G is the gravitational constant. When the virial temperature of a cluster is much larger than that of the gas accreted by the cluster, a shock forms near the virial radius of the cluster (Takizawa, Mineshige 1998; Cavaliere et al. 1998). The ICM temperature inside the shock is related to that of the preshock gas (T_p) and is approximately given by

$$T_\mathrm{ICM} = T_\mathrm{vir} + \frac{3}{2}T_\mathrm{p} \tag{18}$$

(Cavaliere et al. 1998). Since we assume that the density profile of dark matter is given by equation (13) with $a = 2.4$, the density profile of ICM is given by

$$\rho_\mathrm{ICM}(r) = \rho_\mathrm{ICM,vir}\frac{[1+(r/r_\mathrm{c})^2]^{-3b/2}}{[1+(r_\mathrm{vir}/r_\mathrm{c})^2]^{-3b/2}}\,, \tag{19}$$

where $b = (2.4/3)T_\mathrm{vir}/T_\mathrm{ICM}$ (Bahcall, Lubin 1994). We choose $3T_1/2 = 0.8$ keV according to Paper I. The normalization $\rho_\mathrm{ICM,vir}$ is determined by the relation $f_\mathrm{ICM} = M_\mathrm{ICM}/M_\mathrm{vir}$.

When $T_\mathrm{vir} \lesssim (3/2)T_\mathrm{p}$, a shock does not form but the gas accreted by a cluster adiabatically falls into the cluster. The ICM profile for $r < r_\mathrm{vir}$ is obtained by solving the equation of hydrostatic equilibrium and is approximately given by

$$\rho_\mathrm{ICM}(r) = \rho_\mathrm{ICM,vir}\left[1+\frac{3}{A}\ln\left(\frac{r_\mathrm{vir}}{r}\right)\right]^{3/2}\,, \tag{20}$$

where

$$A = \frac{15K_0\rho_\mathrm{ICM,vir}^{2/3}}{8\pi G\rho_\mathrm{mv,iso}r_\mathrm{vir}^2} \tag{21}$$

(Balogh et al. 1999a). Equation (20) is for the isothermal dark-matter distribution (r^{-2}), which is a little different from that we adopted ($r^{-2.4}$). We assume equation (20) as an approximation because there is no analytical solution for the dark-matter distribution of $r^{-2.4}$ (Paper I). The parameter $\rho_\mathrm{ICM,vir}$ is determined by the relation $f_\mathrm{ICM} = M_\mathrm{ICM}/M_\mathrm{vir}$. In section 3, we use the profile (19) for $T_\mathrm{vir} > 3T_1/2$ (= 0.8 keV) and the profile (20) for $T_\mathrm{vir} < 3T_1/2$. We refer to this ICM distribution as 'the heated ICM distribution'. From observations, we use the value of $K_0 = 0.37K_{34}$, which is assumed to be independent of cluster mass (Balogh et al. 1999a). The heated ICM distribution is flatter than non-heated ICM distribution, and gives a smaller ICM density at the cluster center, which has also been demonstrated by numerical simulations including non-gravitational heating (Navarro et al. 1995; Bialek et al. 2001).

2.2.2. A radially infalling galaxy

We consider a radially infalling disk galaxy accreted by a cluster with dark matter, that is, the first infall to the cluster. The initial velocity of the model galaxy, v_i, is given at $r = r_\mathrm{vir}$, and it is

$$\frac{v_{\rm i}^2}{2} = \frac{GM_{\rm vir}}{r_{\rm vir}} - \frac{GM_{\rm vir}}{r_{\rm ta}}\,, \tag{22}$$

where $r_{\rm ta}$ is the turnaround radius of the cluster. Assuming that $r_{\rm ta} = 2\,r_{\rm vir}$ based on the virial theorem, the initial velocity is

$$v_{\rm i} = \sqrt{\frac{GM_{\rm vir}}{r_{\rm vir}}}\,. \tag{23}$$

The galaxy falls freely toward the cluster center.

As the velocity of the galaxy increases, the ram-pressure from ICM also increases. The condition of ram-pressure stripping is

$$\begin{aligned}\rho_{\rm ICM} v_{\rm rel}^2 &> 2\pi G \Sigma_\star \Sigma_{\rm HI} \\ &= v_{\rm rot}^2 R^{-1} \Sigma_{\rm HI} \\ &= 2.1\times 10^{-11} {\rm dyn\,cm^{-2}} \left(\frac{v_{\rm rot}}{220\,{\rm km\,s^{-1}}}\right)^2 \\ &\quad \times \left(\frac{r_{\rm gal}}{10\,{\rm kpc}}\right)^{-1} \left(\frac{\Sigma_{\rm HI}}{8\times 10^{20} m_{\rm H}\,{\rm cm^{-2}}}\right)\,,\end{aligned} \tag{24}$$

where $v_{\rm rel}$ is the relative velocity between the galaxy and the ICM, $\Sigma_\star$ is the gravitational surface mass density, $\Sigma_{\rm HI}$ is the surface density of the H I gas, $v_{\rm rot}$ is the rotation velocity, and $r_{\rm gal}$ is the characteristic radius of the galaxy (Gunn, Gott 1972; Fujita, Nagashima 1999). The original derivation by Gunn and Gott (1972) assumed a disk mass distribution, but Abadi et al. (1999) have numerically confirmed that this analytic relation provides a good approximation even for a more realistic mass distribution. Note that equation (24) includes the rotation velocity of the galaxy, and thus it implicitly takes account of the gravity from the dark-matter halo surrounding the galaxy. From equation (24) and observations, we can show the dependence of ram-pressure stripping on the galaxy mass for a given $\Sigma_{\rm HI}$. Shen et al. (2003) showed that the typical radius and mass of late-type galaxies have the relation $R \propto M_{\rm gal}^{0.4}$ for $M_{\rm gal} \gtrsim 10^{10.6}\,M_\odot$ from the Sloan Digital Sky Survey (SDSS). Since $v_{\rm rot}^2 \propto M_{\rm gal}/R$, we obtain $v_{\rm rot}^2 R^{-1} \propto M_{\rm gal}^{0.2}$. This means that ram-pressure stripping is more effective for a smaller galaxy [equation (24)]. We define the cluster radius at which condition (24) is satisfied for the first time as the stripping radius, $r_{\rm st}$. Since we assume that the ICM is nearly in pressure equilibrium for $r < r_{\rm vir}$, the relative velocity, $v_{\rm rel}$, is equivalent to the velocity of the galaxy relative to the cluster, v, for $r < r_{\rm vir}$. We take account of cluster growth while the galaxy moves from $r = r_{\rm vir}$ to $r_{\rm st}$ according to Paper I.

2.3. Evaporation

Thermal evaporation of cold gas within galaxies by hot ICM was studied by Cowie and Songaila (1977), although it seems that the effect of evaporation has been forgotten for a long time. Basically, the model presented here is the same as that of Cowie and Songaila (1977).

The energy flux from the hot ICM surrounding a galaxy via thermal conduction is given

by

$$L = -4\pi r^2 \kappa \frac{dT}{dr}\,, \tag{25}$$

where κ is the conduction rate and is given by $\kappa = \kappa_0 T^{5/2}$. We assume that $\kappa_0 = 5 \times 10^{-7}$ erg cm^{-1} s^{-1} K$^{-3.5}$. In general, we do not need to consider the saturation of thermal conduction if the galaxy is at the center of the cluster because the ICM density is sufficiently large. In this case, equation (25) is approximated by

$$|L| \approx 4\pi r_{\rm gal} \kappa_0 T_{\rm ICM}^{7/2}\,. \tag{26}$$

Thus, the time scale of the evaporation of cold gas in a galaxy is written as

$$t_{\rm cond} \approx \frac{3}{2}\frac{k_{\rm B}T_{\rm ICM}}{\mu m_{\rm H}}\frac{M_{\rm cold}}{|L|} = \frac{3}{8\pi}\frac{k_{\rm B}M_{\rm cold}}{\mu m_{\rm H} r_{\rm gal}\kappa_0 T_{\rm ICM}^{5/2}}\,, \tag{27}$$

where $M_{\rm cold}$ is the mass of cold gas in the galaxy. We define neutral and molecular gas confined in a galactic disk as cold gas.

On the other hand, if a galaxy is not at the cluster center, the density of the surrounding ICM would be small and the saturation of thermal conduction could be important. The saturated flux is given by

$$|L_{\rm sat}| = 4\pi r_{\rm gal}^2 \times 0.4 n_{\rm e} k_{\rm B} T_{\rm ICM} \left(\frac{2k_{\rm B}T_{\rm ICM}}{\pi m_{\rm e}}\right)^{1/2}\,, \tag{28}$$

where $n_{\rm e}$ is the electron number density and $m_{\rm e}$ is the electron mass (Cowie, McKee 1977). We define the *cluster* radius, $r_{\rm sat}$, as the one where $|L| = |L_{\rm sat}|$. For $r < r_{\rm sat}$, thermal conduction is not affected by the saturation. On the other hand, the flux through thermal conduction is limited by the saturation for $r > r_{\rm sat}$.

2.4. Galaxy Mergers

If a galaxy is not at the center of a dark halo (here, a dark halo means a cluster, a subcluster, a group, or its progenitor), it is affected by dynamical friction and gradually falls toward the halo center. The galaxy is expected to merge with another galaxy that has already been at the halo center. In this paper, we treat only galaxy mergers in which one of the galaxies is at the halo center. Mergers between galaxies that are not at the halo center (satellite galaxies) are not important unless the velocity dispersion of the halo is comparable to the rotation velocities of the galaxies (Binney, Tremaine 1987).

The time scale of dynamical friction is given by

$$t_{\rm fric} \approx \frac{1.17}{\ln\Lambda}\frac{r_0 v_{\rm c}}{GM_{\rm gal}}\,, \tag{29}$$

where $\ln\Lambda$ is the Coulomb logarithm, r_0 is the initial position of a galaxy in a halo, $v_{\rm c}$ is the circular velocity of the halo, and $M_{\rm gal}$ is the mass of the galaxy falling into the halo center (Binney, Tremaine 1987). The Coulomb logarithm can be approximated by $\ln\Lambda \approx$

$(1/2)\ln(1+M_{\rm gal}^2/M_{\rm vir}^2)$ (Binney, Tremaine 1987). Equation (29) does not depend on the galaxy types. We set $r_0 = r_{\rm h}$, where $r_{\rm h}$ is the half-mass radius of the halo and it is given by

$$r_{\rm h} = r_{\rm vir}(1/2)^{1/(3-a)} \tag{30}$$

for the dark matter distribution we adopt [equation (13)]. We assume that $v_{\rm c}$ is the circular velocity at $r = r_{\rm h}$.

3. Results

As a cosmological model, we consider a cold dark matter model with a non-zero cosmological constant (ΛCDM model). The cosmological parameters are $h = 0.7$, $\Omega_0 = 0.25$, $\lambda_0 = 0.75$, and $\sigma_8 = 0.8$. The mass of a model cluster at $z = 0$ is $M_0 = 1\times 10^{15}\,M_\odot$. Among the progenitors, the typical mass of the main cluster at $z > 0$ is given by $M_{\rm vir} = \bar{M}_{\rm EPS}(z|M_0, 0)$. On the other hand, the average mass of the subclusters is given by $M_{\rm vir} = \bar{M}_{\rm SPS}(z|M_0, 0)$. The radius of the precluster region, R_0, is given by $R_0 = (3M_0/4\pi\bar{\rho})^{1/3}$, where $\bar{\rho}$ is the current mean mass density of the universe. Note that R_0 is different from the viral radius of the cluster, $r_{\rm vir}$. We take $R_{\rm in} = 0.7R_0$ and $R_{\rm out} = R_0$ in equation (6). If we take $R_{\rm in} = 0.5R_0$ $(0.9R_0)$, the average mass of the subclusters becomes larger (smaller) only by $\sim 20\%$. Thus, the following results are not very sensitive to the choice of $R_{\rm in}$.

Figure 1 shows the evolution of cluster masses. Since matter is almost uniformly distributed in the very early universe, we expect that when the mass of the main cluster satisfies the relation $M_{\rm vir}/M_0 = (R_{\rm in}/R_0)^3$, the subclusters begin to be included in the main cluster and become the subhalos. For the parameters we adopted, the subclusters are absorbed by the main cluster at $z \lesssim 0.4$.

At $z = 0.5$, the mass of the main cluster is $3\times 10^{14}\,M_\odot$, which is close to the masses of well-known clusters observed at $z \sim 0.5$ (Schindler 1999). At $z = 0.5$, the average mass of subclusters is $M_{\rm vir} = 6.7\times 10^{13}\,M_\odot$ and is on the mass scale of galaxy groups. In order to compare these subclusters with groups at low redshift, we also study the evolution of the main component of group progenitors with the present mass of $M_0 = 6.7\times 10^{13}\,M_\odot$. The mass at $z > 0$ is given by $M_{\rm vir} = \bar{M}_{\rm EPS}(z|M_0, 0)$ and is also shown in figure 1.

3.1. Ram-Pressure Stripping and Strangulation

Since we are interested in galaxies at high redshift, we investigate relatively large galaxies that can be observed in detail. We consider two model galaxies. From now on, we mostly adopt observed parameters of the Galaxy for a bigger galaxy and those of M 33 for a smaller galaxy. We will show that the results are not sensitive to the galaxy properties, not only for ram-pressure stripping, but also for evaporation. In this paper, we focus on the environmental effects on galaxies; the evolutionary effects of galaxies themselves will be discussed in a forthcoming paper. The parameters for a bigger model galaxy are $v_{\rm rot} = 220\,{\rm km\,s^{-1}}$, $r_{\rm gal} = 10$ kpc, and

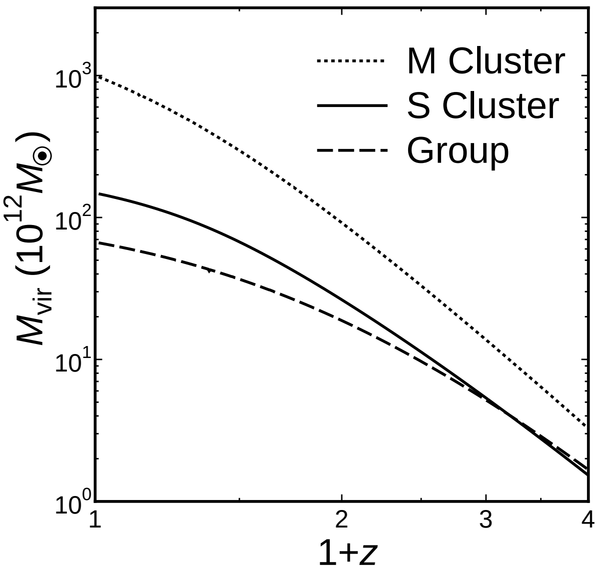

Fig. 1. Mass evolution of a main cluster (dotted line), a typical subcluster (solid line), and a group (dashed line).

$\Sigma_{\rm HI} = 8 \times 10^{20} m_{\rm H}\,{\rm cm}^{-2}$ (Spitzer 1978). The parameters for a smaller model galaxy are $v_{\rm rot} = 105\,{\rm km\,s}^{-1}$, $r_{\rm gal} = 5$ kpc, and $\Sigma_{\rm HI} = 14 \times 10^{20} m_{\rm H}\,{\rm cm}^{-2}$ (Huchtmeier, Richter 1988; Sofue et al. 1999). In terms of H I gas, these galaxies are typical for their luminosities (Huchtmeier, Richter 1988).

We show the evolutions of $r_{\rm st}/r_{\rm vir}$ in figures 2 (the bigger galaxy) and 3 (the smaller galaxy). Since cold gas in a galaxy is almost instantaneously stripped by ram-pressure (Quilis et al. 2000), $r_{\rm st}/r_{\rm vir}$ should be related to the fraction of galaxies affected by ram-pressure stripping in a cluster. In the models of non-heated ICM, $r_{\rm st}/r_{\rm vir}$ increases with z for all mass evolution models, contrary to an expectation that the efficiency of ram-pressure stripping is low in cluster progenitors at high redshift because their masses are small and thus galaxy velocities in them are small. The reason for the increase of $r_{\rm st}/r_{\rm vir}$ at high redshift in our model is that the average mass density of the progenitors, $\rho_{\rm vir}$, is large compared to that of clusters or groups at $z = 0$. In our model, the evolution of the average density can be approximated by $\rho_{\rm vir} \propto (1 + z)^3$. If $\rho_{\rm ICM} \propto \rho_{\rm vir}$, the large mass density leads to large ram-pressure on galaxies although the masses of the progenitors and the velocities of the galaxies in them decrease at higher redshift. Taking the subcluster as an example, $M_{\rm vir} \propto (1 + z)^{-3.8}$ approximately (figure 1). Thus, the virial radius is given by $r_{\rm vir} \propto (M_{\rm vir}/\rho_{\rm vir})^{1/3} \propto (1 + z)^{-2.3}$ and the typical velocity of galaxies in it is given by $v \propto (M_{\rm vir}/r_{\rm vir})^{1/2} \propto (1 + z)^{-0.77}$. Therefore, the ram-pressure is represented by $P_{\rm ram} \propto \rho_{\rm ICM} v^2 \propto \rho_{\rm vir} v^2 \propto (1 + z)^{1.5}$. The mass decrease rates of the subcluster and the group are smaller than that of the main cluster (figure 1). This keeps the velocities of galaxies in the subcluster and the group relatively large even at high redshift. This is the reason why $r_{\rm st}/r_{\rm vir}$ of the subcluster and the group increases more rapidly with z than that of the main cluster.

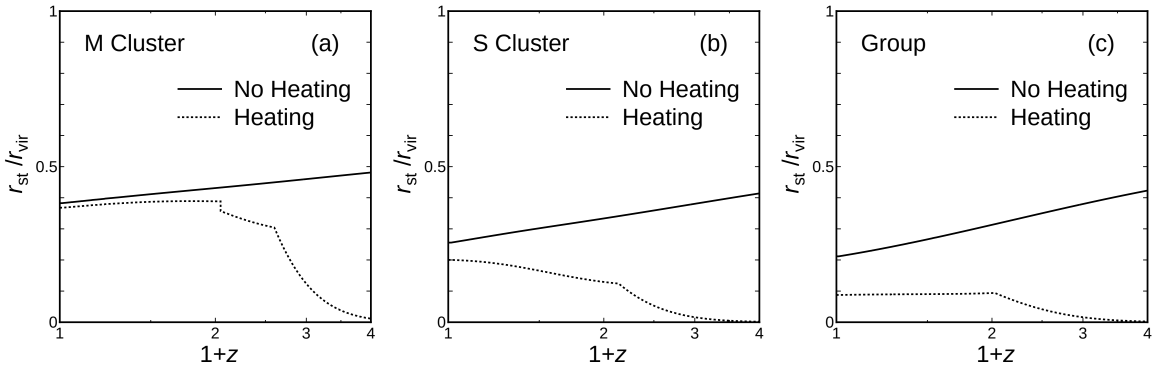

Fig. 2. Evolution of stripping radii, $r_{\rm st}$, normalized by the virial radii, $r_{\rm vir}$, for a bigger galaxy in a (a) main cluster, (b) subcluster, and (c) group. The solid lines are the results of the non-heated ICM model and the dotted lines are those of the heated ICM model. For $r < r_{\rm st}$, ram-pressure stripping is effective.

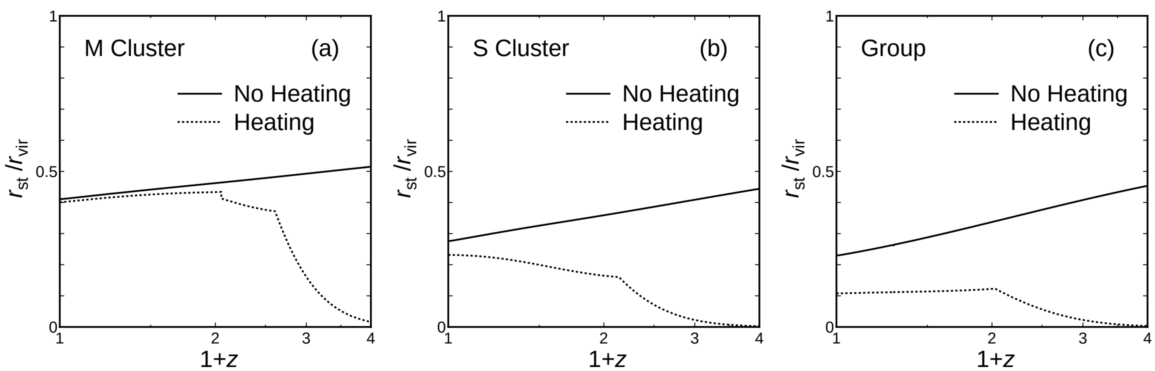

Fig. 3. Same as figure 2, but for a smaller galaxy.

In view of the large $r_{\rm st}/r_{\rm vir}$, it is likely that galaxies in subclusters around the main cluster are affected by ram-pressure stripping before they fall into the main cluster, if the ICM of the subclusters has not been heated non-gravitationally.

Recently, Tormen et al. (2003) studied orbital properties of galaxies in massive clusters by numerical simulations. They showed that the typical pericentric radius of a galaxy for the first passage is about $0.3\,r_{\rm vir}$. This means that most galaxies should be affected by ram-pressure stripping in massive clusters if non-gravitational heating can be ignored (figures 2a and 3a). On the other hand, it is not certain that the results of Tormen et al. (2003) can be applied to the subclusters or groups with smaller masses. If they can, it is shown that ram-pressure stripping takes place for most galaxies for $z \gtrsim 0$–0.5 in the subcluster (figures 2b and 3b) and $z \gtrsim 0.5$–1 in the group (figures 2c and 3c).

The differences between figures 2 and 3 are small. This is because $P_{\rm ram}$ changes very rapidly as a galaxy falls toward the cluster center. Thus, although the thresholds of ram-pressure stripping are different between the bigger and smaller galaxies [Equation (24)], $r_{\rm st}/r_{\rm vir}$ is not significantly affected by the difference.

We can compare ram-pressure stripping in subclusters at high redshift and that in groups at low redshift. The mass of the subcluster at $z = 0.5$ equals that of the group at $z = 0$. However, $r_{\rm st}/r_{\rm vir}$ of the subcluster at $z = 0.5$ is larger than that of the group at $z = 0$ (figures 2b and 2c, or figures 3b and 3c) because of the large mass density of the subcluster. This means that ram-pressure stripping is more effective in the subcluster at $z = 0.5$ than in the group at $z = 0$, although they have the same mass. At higher redshift, the efficiency of ram-pressure stripping increases further.

For a given redshift, $r_{\rm st}/r_{\rm vir}$ of the main cluster is larger than those of the subcluster and the group (figures 2 and 3). This means that ram-pressure stripping is more effective in more massive clusters. This is because the typical velocity of galaxies is larger for more massive clusters (Paper I).

In the model of heated ICM, $r_{\rm st}/r_{\rm vir}$ decreases at high redshift (figures 2 and 3). The changes of the slope are due to the shift in the ICM distribution from equation (19) to (20) and the shift in the ICM fraction from $f_{\rm ICM} = f_{\rm b}$ to $f_{\rm ICM} < f_{\rm b}$ [equation (16)] toward high redshift. Taking the heated ICM model for the main cluster as an example (figures 2a and 3a), the shift in the ICM distribution occurs at $z = 1.0$ and the shift in $f_{\rm ICM}$ occurs at $z = 1.6$. For a given redshift, the ratios $r_{\rm st}/r_{\rm vir}$ in the heated ICM model are smaller than those in the non-heated ICM model because the ICM densities are smaller. The difference is more significant for the subcluster and the group than for the main cluster. This is because the ICM distribution is more flattened in less massive clusters, and especially the ICM densities in the central regions decrease dramatically through non-gravitational heating (subsection 2.2.1). For $z \gtrsim 2$–3, $r_{\rm st}/r_{\rm vir}$ is very small for all mass evolution models because the masses are very small in this redshift range (figure 1). Thus, we predict that ram-pressure stripping does not occur in the redshift range. On the other hand, the ratio $r_{\rm st}/r_{\rm vir}$ in the heated ICM model is almost the same as that in the non-heated ICM model for the main cluster at low redshift (figures 2a and 3a). The ratio $r_{\rm st}/r_{\rm vir}$ for the subcluster at $z = 0.5$ is larger than that for the group at $z = 0$ (figures 2b and 2c or figures 3b and 3c). This appears to show that ram-pressure stripping is *relatively* effective in subclusters at $z \sim 0.5$ even when non-gravitational heating has occurred. However, in the subclusters, the *absolute* fraction of galaxies affected by ram-pressure stripping may not be large. Assuming that a subcluster is located near the virial radius of the main cluster, the tidal acceleration from the main cluster affects the subcluster and the galaxies in it. It is given by

$$a_{\rm t} \approx \frac{G M_{\rm vir,main}}{r_{\rm vir,main}^2}\,, \tag{31}$$

where $M_{\rm vir,main}$ and $r_{\rm vir,main}$ are the virial mass and radius of the main cluster, respectively. We assume that a galaxy falls towards the center of the subcluster on an exactly radial orbit at the virial radius of the subcluster, $r_{\rm vir,sub}$. When the galaxy reaches the center of the subcluster, the orbit of the galaxy in the subcluster would be shifted by $\Delta r \approx a_{\rm t} t_{\rm cent}^2/2$, where $t_{\rm cent}$ is the

time in which the galaxy moves from $r = r_{\rm vir,sub}$ to the center of the subcluster. In our models, for the main cluster and the subcluster at $z = 0.5$, the shift is $\Delta r / r_{\rm vir,sub} \approx 0.2$, although the estimation is very rough. Comparing it with figures 2b or 3b, it is shown that the galaxy can dodge the central region of the subcluster where ram-pressure stripping is effective ($r < r_{\rm st}$) if the ICM has non-gravitationally been heated. We note that if the results of Tormen et al. (2003) claiming that pericentric radii of galaxies are $\sim 0.3\, r_{\rm vir}$ can be applied to the subcluster and group regardless of the redshift, ram-pressure stripping is ineffective for most galaxies in the subcluster and group regardless of redshift if the ICM has non-gravitationally been heated.

In summary, figures 2 and 3 show that if ICM (or the gas accreted by a cluster later on) is heated non-gravitationally at a redshift well over one, ram-pressure stripping does not occur in cluster progenitors including both main clusters and subclusters at $z \gtrsim 2$–3. Moreover, for subclusters around the main cluster, tidal acceleration may prevent galaxies from being affected by ram-pressure stripping even at lower redshift. On the other hand, if the ICM has not been heated non-gravitationally until $z \sim 0$, ram-pressure stripping occurs even at $z \sim 3$ in cluster progenitors.

In the above discussion, we assumed that cold gas remains in a galactic disk until the condition of ram-pressure stripping [equation (24)] is satisfied. This is the case if the gas circulation in a galaxy is confined to the cold gas and stars. However, if warm gas filling in the galactic halo also joins the circulation and is indispensable for the supply of the cold gas, the ram-pressure stripping of the warm gas would be important for the evolution of the galaxy. The low-density warm gas would be stripped before the condition of the ram-pressure stripping of the high-density cold gas is met. After the warm gas is stripped, the cold gas will dissappear in the time scale of star formation of the galaxy, $\tau_\star$, because the gas supply from the warm gas phase is cut and the cold gas in the galaxy is gradually consumed by star formation in the galaxy (strangulation). The time scale of star formation is expected to be $\tau_\star > 1$ Gyr (Okamoto, Nagashima 2003). After the cold gas is consumed completely, the star formation of the galaxy dies out. Note that for a radially infalling galaxy in an actual cluster, rapidly increasing ram-pressure decreases the star-formation time scale and increases the star-formation efficiency of molecular gas in the galaxy significantly (Elmegreen, Efremov 1997; Fujita, Nagashima 1999). These accelerate the consumption of the cold gas. However, if stripping is ignored, the time scale of the gas consumption, $\tau_\star$, is not likely to be smaller than Gyr even if the gas compression by ram-pressure is considered (figures 3 and 4 in Fujita, Nagashima 1999). On the other hand, once the condition of ram-pressure stripping is satisfied, the cold gas of a galaxy is abruptly removed and the star-formation activity of the galaxy is turned off in a very short time because there is no source of stars any longer ($\sim 10^8$ yr; Fujita, Nagashima 1999; Quilis et al. 2000). Thus, when we assume that for a galaxy falling into a cluster from the maximum expansion radius of the cluster, the time scale of the warm gas stripping, $t_{\rm wst}$, is limited to the time in which the galaxy moves from $r = r_{\rm vir}$ to $r = r_{\rm st}$. Therefore, for the galaxy, the maximum time

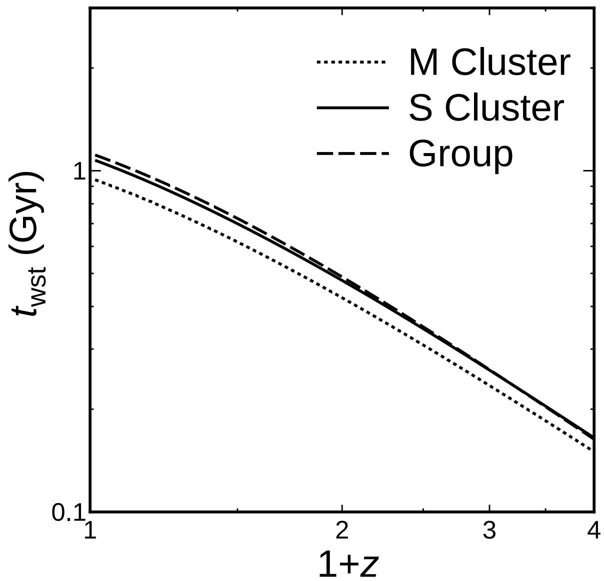

Fig. 4. Maximum time scale allowed for strangulation or evaporation for a main cluster (dotted line), a subcluster (solid line), and a group (dashed line).

scale of the decrease of the star-formation rate when the contribution of warm gas to the gas circulation in the galaxy is considered is represented by $t_{\rm stra} = \min(\tau_\star, t_{\rm wst})$.

Figure 4 shows the redshift dependence of $t_{\rm wst}$ for the non-heated ICM model. Since $t_{\rm wst} \lesssim 1$ Gyr, we expect that $t_{\rm wst} \lesssim \tau_\star$ and $t_{\rm stra} = t_{\rm wst}$, especially when z is large. This means that for galaxies infalling from the outside of a cluster or its progenitors, ram-pressure stripping of the cold gas cannot be avoided if their orbits are close to radial ones. The maximum time scale of the decrease of the star-formation rates ($t_{\rm stra} < 1$ Gyr) will be useful to be compared with observations. Okamoto and Nagashima (2003) conducted N-body simulations combined with a semi-analytic model of galaxy formation. They concluded that ram-pressure stripping does not affect the galaxy evolution in clusters. However, it may be too early to conclude as they did because they did not consider the ram-pressure stripping in subclusters. Calculations including the effect of ram-pressure stripping in subclusters would be interesting.

For the heated ICM model, $t_{\rm wst}$ is not much different from that for the non-heated ICM model, because it takes little time for a galaxy to cross the central region of a cluster and thus the difference of $r_{\rm st}$ does not much affect $t_{\rm wst}$. Since $r_{\rm st}/r_{\rm vir}$ in the heated ICM model is very small for the main cluster at $z \gtrsim 3$ and for the group at $z \gtrsim 2$ (figures 2 and 3), ram-pressure stripping of cold gas may not occur at these redshifts. For the subcluster, ram-pressure stripping may not take place even at lower redshift, because the tidal force from the main cluster may have galaxies elude the central region of the subcluster where ram-pressure stripping is effective [equation (31)]. In these cases, only warm gas stripping or strangulation may occur. Here, we would like to emphasize that *even if future observations such as the search for K+A galaxies*

show that ram-pressure stripping does not take place in subclusters or main clusters at high redshift, it is not an obvious result. The small masses of the subclusters or main clusters are not the only reason. It requires additional reasons such as non-gravitational heating and/or tidal acceleration.

3.2. Evaporation

A galaxy at the center of a cluster does not move relative to the cluster. Thus, it is not affected by ram-pressure stripping, strangulation, and dynamical friction, although it may be the target of other galaxies falling through dynamical friction. However, even if the central galaxy is not affected by these mechanisms, it would be heated by the surrounding hot ICM via thermal conduction. The time scale in which cold gas in a galaxy is evaporated is represented by $t_{\rm cond}$ [equation (27)] and is presented in figures 5 and 6 for a bigger and a smaller galaxy, respectively. In these calculations, we assumed that $r_{\rm gal} = 10$ kpc and $M_{\rm cold} = 5\times 10^9\ M_\odot$ for the bigger galaxy, and $r_{\rm gal} = 5$ kpc and $M_{\rm cold} = 4\times 10^9\ M_\odot$ for the smaller galaxy. We also assumed that $T_{\rm ICM} = T_{\rm vir}$. We ignore the gas supply from the ICM to the central galaxy through a cooling flow. Figures 5 and 6 show that $t_{\rm cond}$ rapidly decreases as z decreases. This is because $t_{\rm cond}$ is very sensitive to $T_{\rm ICM}$ [equation (27)] and $T_{\rm ICM}$ increases as the mass of a cluster (or a subcluster or a group) increases. Because of the sensitivity, the results do not much depend on the deference of galaxy characters (figures 5 and 6). In these figures, the Hubble time, $t_{\rm H}$, is also presented. At low redshift, figures 5 and 6 show that $t_{\rm cond} \ll t_{\rm H}$ in some cases, and thus the cold gas in a galaxy is evaporated soon after the galaxy forms in the cluster or its progenitors. Therefore, we also show $t'_{\rm cond} = t_{\rm cond} + t_{\rm form}$ in the figures, where $t_{\rm form}$ is the Hubble time when the galaxy forms at $z = z_{\rm form}$. If $t'_{\rm cond} < t_{\rm H}$ at a given redshift, the cold gas in a galaxy has been evaporated by the redshift. Note that $t_{\rm cond}$ corresponds to $t'_{\rm cond}$ when $z_{\rm form} = \infty$. For the bigger galaxy in the subcluster, the evaporation is effective at $z \lesssim 0.4$ and 0.6 if $z_{\rm form} = 1$ and 2, respectively (figure 5b). For the smaller galaxy in the subcluster, the evaporation is effective at $z \lesssim 0.3$ and 0.4 if $z_{\rm form} = 1$ and 2, respectively (figure 6b). This means that the evaporation may be developing in the subclusters around the main clusters observed at $z \sim 0.5$. However, since $t_{\rm cond} \gtrsim 2$ Gyr at the redshift when the condition $t'_{\rm cond} \lesssim t_{\rm H}$ is satisfied (figures 5b and 6b), the truncation of star formation in the galaxy proceeds much more slowly than those by ram-pressure stripping and strangulation accompanied by ram-pressure stripping at the end. If gas consumption by star formation is considered, the truncation by evaporation would take a less time.

For the main cluster, evaporation begins to be effective at higher redshift. Figure 5a and 6a indicate that cold gas in galaxies should have been evaporated in massive clusters at $z \sim 1$, although galaxies at the centers of massive clusters are not disk galaxies but mostly cD galaxies with little cold gas. For the group, evaporation becomes effective at lower redshift (figures 5c and 6c). Thus, it may be undergoing at $z \sim 0$ and the situation may be similar to

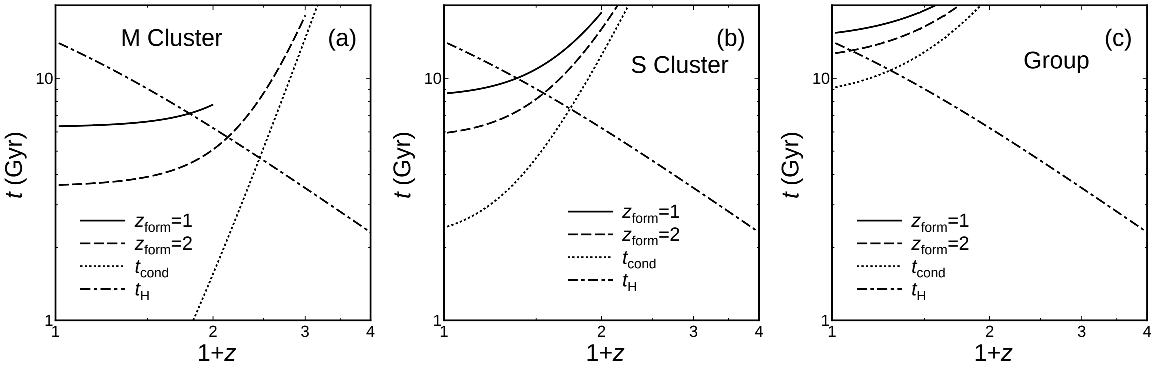

Fig. 5. Time scales of thermal conduction for a bigger galaxy in a (a) main cluster, (b) subcluster, and (c) group. The solid and dashed lines show $t'_{\rm cond} = t_{\rm cond} + t_{\rm form}$ when $z_{\rm form} = 1$ and 2, respectively. The dotted and dot-dashed lines show $t_{\rm cond}$ and the Hubble time $t_{\rm H}$, respectively. For $t'_{\rm cond} \lesssim t_{\rm H}$, thermal conduction is effective.

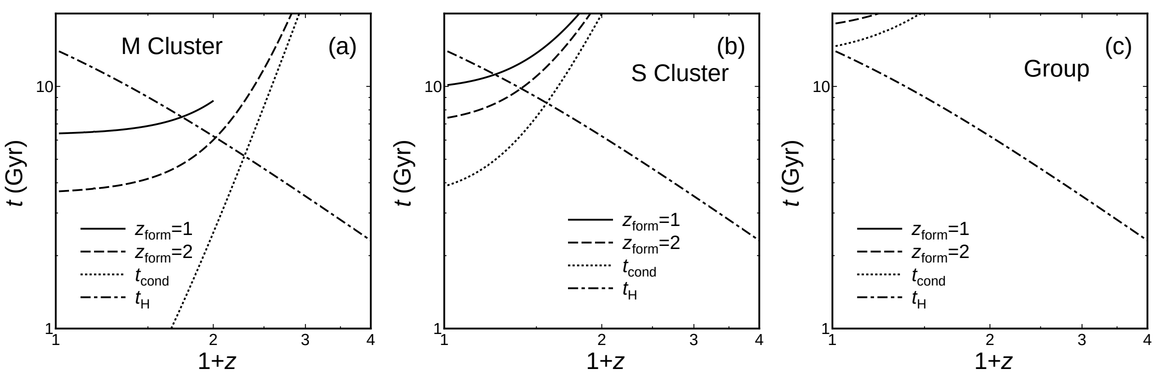

Fig. 6. Same as figure 5, but for a smaller galaxy.

that of the subclusters observed at $z \sim 0.5$.

We investigate whether evaporation has an influence on galaxies being *not* at the center of a cluster (or a subcluster or a group). Figures 7 and 8 show $r_{\rm sat}$ normalized by $r_{\rm vir}$. For the main cluster, $r_{\rm sat}/r_{\rm vir} < 1$ at $z \lesssim 0.7$–1. Because of saturation, the energy flux via thermal conduction is smaller than equation (26) at $r > r_{\rm sat}$. The time scale of evaporation by the *saturated* heat flux [equation (28)] is $\sim$ 1–3 Gyr around the viral radius of the main cluster for $z \lesssim 0.7$–1. Since the time scale of evaporation is larger than $t_{\rm wst}$ (figure 4), we expect that ram-pressure stripping becomes effective before the evaporation affects the cold gas of a galaxy if the galaxy has fallen directly from the outside of the cluster. (As discussed in section 4, this is inconsistent with the observations of CNOC clusters.) For the subcluster, $r_{\rm sat}/r_{\rm vir} > 1$ except for the non-heated ICM model at very low redshift (figures 7b and 8b) and for the group, $r_{\rm sat}/r_{\rm vir}$ is always larger than one. Therefore, we can conclude that evaporation is effective in almost all regions of the subcluster for $z \lesssim 0.5$ and in all regions of the group for $z \sim 0$ if ram-pressure stripping is ignored (figures 5b, 5c, 6b, and 6c). As mentioned in subsection 3.1,

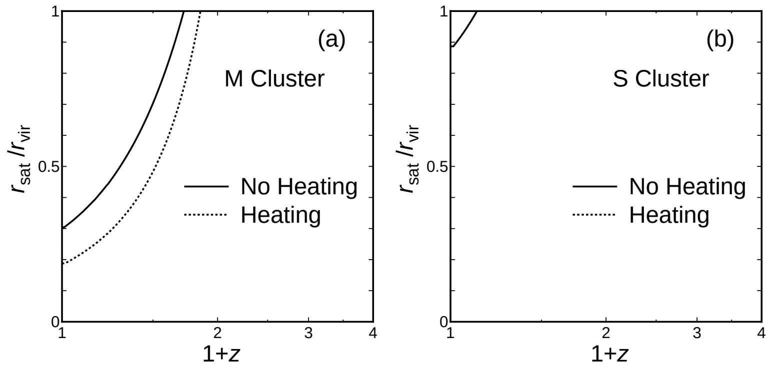

Fig. 7. Radii where thermal conduction is saturated, $r_{\rm sat}$, normalized by viral radii, $r_{\rm vir}$, for a bigger galaxy in a (a) main cluster, and (b) subcluster. The solid and dashed lines show the non-heated and the heated ICM models, respectively. For $r < r_{\rm sat}$, thermal conduction is not saturated. For the model group, $r_{\rm sat}/r_{\rm vir} > 1$ regardless of z.

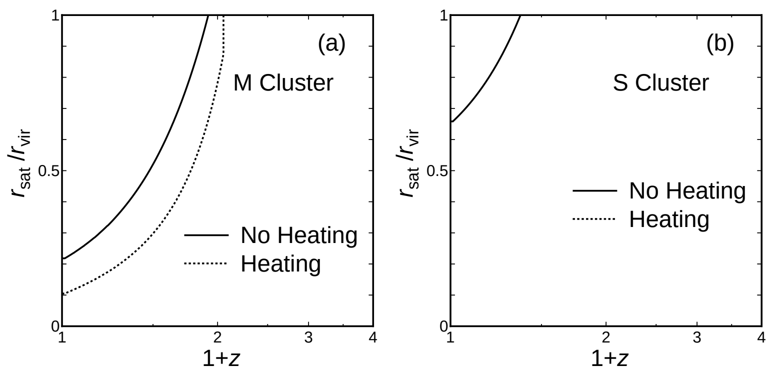

Fig. 8. Same as figure 7, but for a smaller galaxy.

ram-pressure stripping may not occur in subclusters, if non-gravitational heating alters the ICM distributions and the orbits of galaxies are affected by tidal acceleration from the main cluster. In this case, cold gas in a galaxy gradually disappears on a time scale of $t_{\rm cond} \sim 2$–7 Gyr (for $z \lesssim 0.5$) without being affected by ram-pressure stripping, while the galaxy circulates around the subcluster center several times (figures 5b and 6b). For the group, the time scale of evaporation ($t_{\rm cond} \sim 10$ Gyr at $z \sim 0$) is much larger than the dynamical time scale of the group (~ 2 Gyr at $z \sim 0$). Thus, we may need to consider the evolution of the group before we conclude evaporation of the galaxy in the group.

3.3. Galaxy Mergers

After a galaxy is caught by a massive dark halo, its orbit will be affected by dynamical friction. The orbit gradually shrinks and the galaxy merges with the central galaxy of the halo on a time scale of $t_{\rm fric}$. As mentioned in subsection 2.4, we consider mergers in which one of the merging galaxies is at the halo center and that the mass is sufficiently large. We also assume

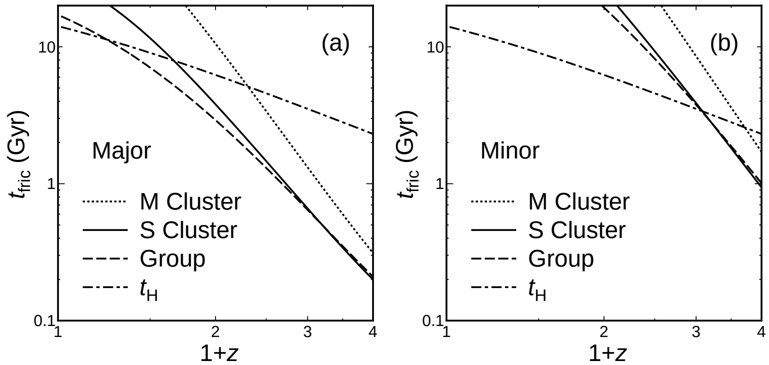

Fig. 9. Time scales of dynamical friction for a main cluster (dotted line), a subcluster (solid line), and a group (dashed line). The mass of a satellite galaxy is (a) $M_{\rm gal} = 2 \times 10^{11}\ M_\odot$, and (b) $M_{\rm gal} = 2 \times 10^{10}\ M_\odot$. The mass of the central galaxy should be larger than these values. The dot-dashed lines show the Hubble time, $t_{\rm H}$. For $t_{\rm fric} \lesssim t_{\rm H}$, galaxy mergers are effective.

that the mass of another galaxy falling into the halo center is $M_{\rm gal} = 2 \times 10^{11}\ M_\odot$ (figure 9a) and $2 \times 10^{10}\ M_\odot$ (figure 9b). These masses include those of the individual galactic halos surrounding the infalling galaxies. The mass of the bigger galaxy ($2 \times 10^{11}\ M_\odot$) is based on the traditional Galaxy mass (e.g. Allen 1973), although recent studies show that the mass of the Galaxy is much larger (Sakamoto et al. 2003). However, most of the mass resides in the outer halo region, and it would tidally be stripped in a cluster. Thus, we assumed the traditional value. In figure 9, we present $t_{\rm fric}$ for our model cluster, subcluster, and group. The Hubble time $t_{\rm H}$ is also depicted. Galaxy mergers are effective when $t_{\rm fric} \lesssim t_{\rm H}$. When $M_{\rm gal} = 2 \times 10^{11}\ M_\odot$ ($2 \times 10^{10}\ M_\odot$), we do not expect galaxy mergers at $z \lesssim 1.3$ (2.7) in the main cluster and at $z \lesssim 0.6$ (2.1) in the subcluster.

Since the masses of most galaxies are smaller than $2 \times 10^{11}\ M_\odot$, the results indicate that galaxy mergers had already ceased in the subclusters observed around massive clusters at $z \lesssim 0.6$. For the main cluster, galaxy mergers have stopped at higher redshift, because the velocities of galaxies are large in the cluster. Figure 9 suggests that galaxies at the centers of massive clusters (cD galaxies) formed at $z \gtrsim 1$ if they formed through galaxy mergers. For the group in figure 9a, galaxy mergers had recently stopped at $z \sim 0.2$. Thus, the situation is similar to that of the subclusters observed at $z \sim 0.5$.

4. Discussion

Star-formation histories of galaxies in clusters and subclusters may tell us the relation between environmental effects and the truncation of the star-formation activities of the galaxies. Unfortunately, there have not been detailed observations about the star-formation histories of galaxies in subclusters around the main clusters. Thus, we first discuss the star-formation histories of galaxies in main clusters, and then infer what has happened in the subclusters.

Sharp truncation of star formation ($\lesssim 10^9$ yr) would lead to an abundant population of galaxies with strong Balmer lines, but no nebular emission lines (K+A galaxies, but see Miller, Owen 2001). Large fractions of K+A galaxies have been reported in some main clusters at $0.4 \lesssim z \lesssim 0.6$, in particular by the MORPHS collaboration (Dressler et al. 1999; Poggianti et al. 1999). On the other hand, these galaxies appear to be rare in the CNOC sample of very luminous X-ray clusters studied by Balogh et al. (1999b). Moreover, Kodama and Bower (2001) analyzed CNOC clusters, and indicated that if star formation declines on a relatively long time scale ($1-3$ Gyr) after accretion to the clusters, the galaxy accretion history that they infer is consistent from cluster to cluster and matches well the distribution of galaxies in the color-magnitude diagram expected in simple theoretical models. On the other hand, models in which star formation is abruptly truncated as galaxies are accreted by the cluster have difficulty in reproducing the observed color distribution. It is still unclear whether this apparent disagreement between the MORPHS and the CNOC clusters is a result of the procedure used to select the spectroscopic sample, the effects of dust obscuration, or perhaps a genuine effect of the dependence of star-formation rates on other cluster properties such as X-ray luminosity or temperature (Balogh et al. 1999b). In the following, we mostly discuss those distant clusters observed at $z \sim 0.5$.

If the former observational results can be applied to most clusters, ram-pressure stripping is the most promising candidate of the mechanism that suppresses star formation, because ram-pressure stripping removes cold gas in a galactic disk almost instantaneously (Abadi et al. 1999; Quilis et al. 2000), and as a result, the star-formation rate of the galaxy drops rapidly on a time scale of $\sim 10^8$ yr (Fujita, Nagashima 1999). Moreover, ram-pressure stripping naturally accounts for the observed trend that fractions of blue galaxies are systematically lower for rich clusters than for poor clusters at a given redshift (Paper I; Margoniner et al. 2001; Goto et al. 2003a).

On the other hand, for the subclusters at $z \sim 0.5$, ram-pressure stripping also seems to be important if the ICM has not been heated non-gravitationally (figures 2b and 3b). Although quantitative discussion may need the knowledge of distribution of galaxy orbits, it is at least more efficient than the groups with the same mass at $z \sim 0$. Ram-pressure stripping in the subclusters could be observed as the existence of K+A galaxies. If they are really observed, it would show that the non-gravitational heating of the ICM has not occurred at that redshift at least for the subclusters.

If the slow decline of star-formation rates of galaxies observed in some main clusters is confirmed for most clusters, it would be difficult to make a compromise with our models. Ram-pressure stripping is effective regardless of non-gravitational heating in the main cluster at $z \lesssim 1$ (figures 2a and 3a). Even if we adopt a strangulation model, ram-pressure stripping starts before strangulation finishes (subsection 3.1), and it leads to a sharp decline of the star-formation rates of galaxies. Bekki et al. (2002) demonstrated numerical simulations and

claimed that warm gas in the halo of a disk galaxy can gradually be stripped by ram-pressure from ICM ($\gtrsim$ Gyr). However, the orbit of a galaxy that they assumed is far from a radial one in spite of the fact that galaxies falling into a cluster for the first time take almost radial orbits.

One possible solution of the problem is that most galaxies had already been affected by strangulation and/or evaporation to some degree in subclusters before they entered the main clusters. If this is the case, the total time in which the galaxies are under the influence of strangulation or evaporation can be larger than $t_{\rm wst}$ shown in figure 4. Thus, strangulation and/or evaporation could be completed before galaxies are affected by ram-pressure stripping, especially when ram-pressure stripping is avoided in subclusters by non-gravitational heating and tidal acceleration from the main cluster (subsection 3.1). In particular, the evaporation scenario works even if all warm gas around a disk galaxy had fallen onto the galactic disk at a relatively high redshift (see Benson et al. 2000). We emphasize that non-gravitational heating, tidal acceleration, or something else had to affect the ICM distributions or the galaxy orbits in subclusters in order to effectively avoid the intensive gas removal through ram-pressure stripping. If cold gas in most galaxies had completely stripped by ram-pressure stripping and their star-formation activities had ceased until they entered main clusters, the expected color distribution of galaxies in clusters may not be consistent with the blue galaxy fractions of the CNOC clusters estimated by Kodama and Bower (2001).

The above 'pre-processing' scenario about the decline of star-formation activities of galaxies is consistent with recent observations. Morphological studies of distant cluster galaxies revealed the presence of an unusual population of galaxies with a spiral morphology and the lack of star-formation activity (Couch et al. 1998; Dressler et al. 1999; Poggianti et al. 1999). These galaxies are called 'passive spiral galaxies'. In particular, Goto et al. (2003b) analyzed the Sloan Digital Sky Survey (SDSS) galaxy catalogue and showed that passive spiral galaxies live at $\sim$ 1–10 cluster-centric virial radius. These galaxies may be the galaxies affected by strangulation and/or evaporation in subclusters around the main clusters, because strangulation and evaporation affect the star-formation activities of spiral galaxies, but not their morphology. In fact, using Suprime-Cam on the Subaru Telescope, Kodama et al. (2001) showed that the color change of galaxies occurs in subclumps well outside the main cluster Abell 851. On the other hand, we should note that the existence of passive spiral galaxies alone can be explained by ram-pressure stripping in subclusters.

Galaxy mergers are thought to be responsible for the morphological changes of galaxies, although they may also induce starburst. We assumed that the mass of the central galaxy of a cluster or a subcluster is larger than the mass of galaxies that are not at the cluster or subcluster center (satellite galaxies) and is $\gtrsim 10^{11}\,M_\odot$. Although the central galaxies of current massive clusters are mostly massive elliptical galaxies, the central galaxies might be massive spiral galaxies in the cluster progenitors when the masses of the progenitors were small.

For the main cluster, mergers between massive galaxies or major mergers are rare at

$z \lesssim 1.3$ (figure 9a). This is because as a cluster grows, the typical velocity of galaxies in the cluster increases and $t_{\rm fric}$ decreases [equation (29)]. Mergers between central galaxies of clusters and galaxies with small mass (minor mergers) had finished even earlier (figure 9b). Thus, for the observed main clusters at $z \lesssim 1$, mergers at the cluster centers should have stopped. Compared with the main cluster, galaxy mergers could occur at a lower redshift in the subclusters (figure 9). Major mergers occur even at $z \sim 0.6$.

Major mergers would create elliptical galaxies (Toomre, Toomre 1972). In fact, theoretical models including major mergers give an excellent explanation for colors and distribution of cluster ellipticals (Kauffmann, Charlot 1998; Okamoto, Nagashima 2001; Nagashima, Gouda 2001; Diaferio et al. 2001). Thus, our model for main clusters (and many other previous studies) shows that the formation of elliptical galaxies at $r \sim 0$ is at $z > 1$. A main cluster might be divided into several clusters at high redshift and elliptical galaxies observed at $r \sim 0$ at present might form in those main clusters. Since major mergers could occur at lower redshift in subclusters (figure 9a), they may be observed in the cluster proximity, even at $z < 1$. We note that using N-body simulations, Ghigna et al. (1998) showed that mergers between haloes in the cluster proximity occur with a frequency of about 5–10% even since $z = 0.5$. However, it is not certain that this frequency corresponds to the merger frequency of galaxies in those halos.

On the other hand, major mergers alone cannot account for the fraction of galaxies with intermediate bulge-to-disk luminosity ratios such as S0 galaxies (Okamoto, Nagashima 2001; Diaferio et al. 2001). Okamoto and Nagashima (2003) indicated that minor mergers may create the galaxies with intermediate bulge-to-disk luminosity ratios because minor mergers do not disrupt galactic disks completely. However, they also indicated that the fraction of the galaxies with intermediate bulge-to-disk luminosity ratios does not evolve with a redshift contrary to observations (Dressler et al. 1997). This is consistent with our prediction that minor mergers had finished at fairly high redshift for both the main cluster and the subcluster ($z \gtrsim 2$; figure 9b). These studies suggest that minor mergers in clusters are not the mechanism of the observed morphological transformation to S0 galaxies at $z \lesssim 1$.

Ram-pressure stripping could darken a galactic disk and increase the bulge-to-disk luminosity ratio of a disk galaxy (Fujita, Nagashima 1999). However, the total luminosity of the galaxy may decrease too much to be observed as a bright massive galaxy (Okamoto, Nagashima 2003, see also Balogh et al. 2002a). Moreover, Kodama and Smail (2001) indicated that the process responsible for the morphological transformation from a spiral to a S0 galaxy takes a relatively long time ($\sim$ 1–3 Gyr) after the galaxy has entered the cluster environment. The time scale would be too long for the morphological transformation by ram-pressure stripping (Fujita, Nagashima 1999). Thus, the morphological transformation may be due to a change of Q-parameter after strangulation (Bekki et al. 2002) or tidal acceleration from a cluster potential on galaxies (Byrd, Valtonen 1990; Valluri 1993; Henriksen, Byrd 1996; Fujita 1998).

Dale et al. (2001) showed that early-type spirals in cluster cores appear to be more perturbed than their counterparts in the cluster peripheries by a factor of 2. This result suggests that early-type spiral galaxies in clusters likely experienced gravitationally induced disturbances as they pass near the cluster cores, In a massive main cluster, cold gas of a disk galaxy may have to be removed or consumed until the galaxy is affected by the tidal acceleration in the central region of the cluster; otherwise the kinetic pressure on the cold gas and the star-formation rate of the galaxy would increase there, which is inconsistent with observations of massive clusters (Fujita 1998). A galaxy may have to pass the cluster (or subcluster) center several times until the morphology is significantly changed. Numerical simulations done by Ghigna et al. (1998) showed that in a cluster, galaxies follow almost radial orbits rather than circular ones even after their first infalls to the cluster. It is to be noted that Gnedin (2003) indicated that the morphological transformation by tidal force may occur even in the outer region of a hierarchically growing cluster. Thus, some of observed S0 galaxies were formed outside the core of a cluster. Recently, Treu et al. (2003) showed that the morphology-density relation of galaxies holds even the outside of a cluster. This suggests that the morphological change does not take place in field regions but in subclusters.

Finally, we point out that some of blue disk galaxies observed in clusters may be galaxies that restart star formation after they have passed the central regions of the clusters. Although the cold gas of these galaxies was once removed by ram-pressure stripping, the galaxies could accumulate cold gas again from the gas ejected from their stars if ram-pressure drops enough. The condition that cold gas is accumulated again is given by

$$\begin{aligned}\rho_{\rm ICM} v_{\rm rel}^2 &< \frac{16}{v_{\rm rel}} \frac{S}{\pi r_{\rm gal}^2} v_{\rm rot}^2 \\ &= 2.0\times 10^{-11} {\rm dyn\ cm^{-2}} \left(\frac{v_{\rm vel}}{500\ {\rm km\ s^{-1}}}\right)^{-1} \\ &\times \left(\frac{S}{6\ M_\odot\ {\rm yr^{-1}}}\right) \left(\frac{r_{\rm gal}}{10\ {\rm kpc}}\right)^{-2} \left(\frac{v_{\rm rot}}{220\ {\rm km\ s^{-1}}}\right)^{2}, \end{aligned} \tag{32}$$

where S is the gas ejection rate from stars (Takeda et al. 1984; Fujita et al. 1999). Comparing equation (24) with equation (32), one finds that the threshold values are very similar for a massive disk galaxy we study. Thus, the gas accumulation and star formation would resume at $r \sim r_{\rm st}$ after the galaxy passed the central region of a cluster. A detailed discussion of the resumed star formation is beyond the scope of this paper, because the orbit of a galaxy that has passed the center of a cluster is gradually affected by gravity from other galaxies and changing potential well of the host cluster. Numerical simulations are needed to follow the orbits of galaxies for a long time. We note that using a numerical simulation, Fujita et al. (1999) showed that the star formation of galaxies is suppressed during a cluster merger, because the ram-pressure on galaxies increases and ram-pressure stripping becomes effective. However, they also showed that after a smaller cluster passed the center of a larger cluster, star

formation resumes because of the decrease of ram-pressure and the accumulation of cold gas in the galaxies. Moreover, from N-body numerical simulations of cluster formation, Balogh et al. (2000) indicated that a significant fraction of galaxies beyond the virial radius of a cluster may have been within the main body of the cluster in the past. These galaxies would resume the star-formation activities.

5. Summary and Conclusions

Using analytical models based on a hierarchical clustering scenario, we have investigated the evolution of massive disk galaxies in clusters. We have considered the effects of cosmological evolution of clusters on galaxy evolution. In particular, we have explored the galaxy evolution in subclusters located around the main cluster. The main conclusions from this work may be summarized as follows:

(i) As long as the spatial distribution of intracluster medium (ICM) follows that of dark matter in a cluster or a subcluster, galaxies are influenced by ram-pressure stripping of the cold disk gas. For a given massive cluster at $z=0$, ram-pressure stripping in the cluster progenitors is more effective at higher redshift although the masses of the cluster progenitors decrease with redshift. This is because the typical mass density of the progenitors increases with the redshift. Even in subclusters, ram-pressure stripping is effective.

(ii) If field galaxies directly fall into a main cluster, the exhaustion of the cold disk gas via star formation, after stripping of the warm diffuse gas in their galactic halos ('strangulation'), would not be completed before ram-pressure stripping of the cold disk gas becomes effective. This limits the time scale in which star-formation rates of the galaxies decline. The maximum time scale is $\lesssim$ Gyr, which is inconsistent with some observations.

(iii) The conflict between the theoretical prediction and the observations may be avoided if the star-formation rates of galaxies had already dropped in subclusters before the subclusters plunged into the main cluster ('pre-processing'). This is consistent with recent observations indicating that the star-formation rates of galaxies are decreased at radii well larger than the virial radii of main clusters.

(iv) The star-formation rates of galaxies in subclusters might have gradually decreased via strangulation and/or evaporation of the cold gas by the surrounding hot ICM, if non-gravitational heating of ICM ('preheating') had changed the ICM distributions of the subclusters, and tidal force from the main cluster prevents the galaxies from being affected by ram-pressure stripping. These may be the mechanism of the pre-processing. In particular, the evaporation scenario is free from the problem that warm gas in galactic halos has not been detected.

(v) It is not obvious whether ram-pressure stripping takes place in subclusters (or main clusters at high redshift) or not. Even if future observations show that ram-pressure stripping does not occur in subclusters (or main clusters at high redshift), their small masses cannot

be the only reason. It requires additional reasons, such as the preheating and/or the tidal acceleration.

(vi) Mergers between a galaxy at the center of a cluster progenitor and that not at the center had mostly finished at $z \gtrsim 1$–2 because the velocities of galaxies increase as the host clusters grow. Thus, galaxy mergers do not appear to be the main cause of the observed morphological transformation from spiral galaxies to S0 galaxies at $z \lesssim 1$.

(vii) The star-formation activity of a galaxy may resume after the galaxy has passed the central region of a cluster and the ram-pressure from the ICM has dropped. This may affect the fraction of blue galaxies in clusters.

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References

Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947

Abraham, R. G., et al. 1996, ApJ, 471, 694

Allen, C. W. 1973, Astrophysical Quantities, 3rd ed. (London; Athlone)

Bahcall, N. A., & Lubin, L. M. 1994, ApJ, 426, 513

Balogh, M. L. et al. 2002a, ApJ, 566, 123

Balogh, M. L., Babul, A., & Patton, D. R. 1999a, MNRAS, 307, 463

Balogh, M., Bower, R. G., Smail, I., Ziegler, B. L., Davies, R. L., Gaztelu, A., & Fritz, A. 2002b, MNRAS, 337, 256

Balogh, M. L., Couch, W. J., Smail, I., Bower, R. G., & Glazebrook, K. 2002c, MNRAS, 335, 10

Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1997, ApJ, 488, L75

Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999b, ApJ, 527, 54

Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, ApJ, 540, 113

Balsara, D., Livio, M., & O'Dea, C. P. 1994, ApJ, 437, 83

Baugh, C. M., Cole, S., & Frenk, C. S. 1996, MNRAS, 283, 1361

Bekki, K., & Couch, W. J. 2003, ApJ, 596, L13

Bekki, K., Couch, W. J., & Shioya, Y. 2002, ApJ, 577, 651

Benson, A. J., Bower, R. G., Frenk, C. S., & White, S. D. M. 2000, MNRAS, 314, 557

Bialek, J. J., Evrard, A. E., & Mohr, J. J. 2001, ApJ, 555, 597

Bicker, J., Fritze-v. Alvensleben, U., & Fricke, K. J. 2002, A&A, 387, 412

Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press), 428

Bond, J. R., Cole, S., Efstathiou, G., & Kaiser, N. 1991, ApJ, 379, 440

Bower, R. G. 1991, MNRAS, 248, 332

Bravo-Alfaro, H., Cayatte, V., van Gorkom, J. H., & Balkowski, C. 2000, AJ, 119, 580

Bravo-Alfaro, H., Cayatte, V., van Gorkom, J. H., & Balkowski, C. 2001, A&A, 379, 347
Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80
Bureau, M., & Carignan, C. 2002, AJ, 123, 1316
Butcher, H., & Oemler, A., Jr. 1978, ApJ, 219, 18
Butcher, H., & Oemler, A., Jr. 1984, ApJ, 285, 426
Byrd, G., & Valtonen, M. 1990, ApJ, 350, 89
Cavaliere, A., Menci, N., & Tozzi, P. 1998, ApJ, 501, 493
Cayatte, V., van Gorkom, J. H., Balkowski, C., & Kotanyi, C. 1990, AJ, 100, 604
Cole, S., Aragon-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, MNRAS, 271, 781
Couch, W. J., Barger, A. J., Smail, I., Ellis, R. S., & Sharples, R. M. 1998, ApJ, 497, 188
Couch, W. J., Balogh, M. L., Bower, R. G., Smail, I., Glazebrook, K., & Taylor, M. 2001, ApJ, 549, 820
Couch, W. J., & Sharples, R. M. 1987, MNRAS, 229, 423
Couch, W. J., Ellis, R. S., Sharples, R. M., & Smail, I. 1994, ApJ, 430, 121
Cowie, L. L., & McKee, C. F. 1977, ApJ, 211, 135
Cowie, L. L., & Songaila, A. 1977, Nature, 266, 501
Dale, D. A., Giovanelli, R., Haynes, M. P., Hardy, E., & Campusano, L. E. 2001, AJ, 121, 1886
Diaferio, A., Kauffmann, G., Balogh, M. L., White, S. D. M., Schade, D., & Ellingson, E. 2001, MNRAS, 323, 999
Dressler, A., et al. 1997, ApJ, 490, 577
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A., Jr. 1999, ApJS, 122, 51
Ellingson, E., Lin, H., Yee, H. K. C., & Carlberg, R. G. 2001, ApJ, 547, 609
Elmegreen, B. G., & Efremov, Y. N. 1997, ApJ, 480, 235
Fasano, G., Poggianti, B. M., Couch, W. J., Bettoni, D., Kjærgaard, P., & Moles, M. 2000, ApJ, 542, 673
Fujita, Y. 1998, ApJ, 509, 587
Fujita, Y. 2001a, ApJ, 550, 612 (Paper I)
Fujita, Y. 2001b, ApJ, 550, L7
Fujita, Y., & Nagashima, M. 1999, ApJ, 516, 619
Fujita, Y., Sarazin, C. L., Nagashima, M., & Yano, T. 2002, ApJ, 577, 11
Fujita, Y., Takizawa, M., Nagashima, M., & Enoki, M. 1999, PASJ, 51, L1
Fukushige, T., & Makino, J. 2001, ApJ, 557, 533
Gavazzi, G., Boselli, A., Pedotti, P., Gallazzi, A., & Carrasco, L. 2002, A&A, 396, 449
Gavazzi, G., Cortese, L., Boselli, A., Iglesias-Paramo, J., Vílchez, J. M., & Carrasco, L. 2003, ApJ, 597, 210
Ghigna, S., Moore, B., Governato, F., Lake, G., Quinn, T., & Stadel, J. 1998, MNRAS, 300, 146
Ghigna, S., Moore, B., Governato, F., Lake, G., Quinn, T., & Stadel, J. 2000, ApJ, 544, 616
Gnedin, O. Y. 2003, ApJ, 589, 752
Goto, T., et al. 2003a, PASJ, 55, 739
Goto, T., et al. 2003b, PASJ, 55, 757

Graham, A. W., Jerjen, H., & Guzmán, R. 2003, AJ, 126, 1787
Gunn, J. E., & Gott, J. R. III 1972, ApJ, 176, 1
Henriksen, M., & Byrd, G. 1996, ApJ, 459, 82
Horner, D. J., Mushotzky, R. F., & Scharf, C. A. 1999, ApJ, 520, 78
Huchtmeier, W. K., & Richter, O.-G. 1988, A&A, 203, 237
Kauffmann, G., & Charlot, S. 1998, MNRAS, 294, 705
Kauffmann, G., Colberg, J. M., Diaferio, A., & White, S. D. M. 1999, MNRAS, 303, 188
Kodama, T., & Bower, R. G. 2001, MNRAS, 321, 18
Kodama, T., & Smail, I. 2001, MNRAS, 326, 637
Kodama, T., Smail, I., Nakata, F., Okamura, S., & Bower, R. G. 2001, ApJ, 562, L9
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692
Lewis, I., et al. 2002, MNRAS, 334, 673
Lloyd-Davies, E. J., Ponman, T. J., & Cannon, D. B. 2000, MNRAS, 315, 689
Loewenstein, M. 2000, ApJ, 532, 17
Lubin, L. M. 1996, AJ, 112, 23
Margoniner, V. E., & de Carvalho, R. R. 2000, AJ, 119, 1562
Margoniner, V. E., de Carvalho, R. R., Gal, R. R., & Djorgovski, S. G. 2001, ApJ, 548, L143
Miller, N. A., & Owen, F. N. 2001, ApJ, 554, L25
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A., Jr. 1996, Nature, 379, 613
Mori, M., & Burkert, A. 2000, ApJ, 538, 559
Mulchaey, J. S. 2000, ARA&A, 38, 289
Mulchaey, J. S., Davis, D. S., Mushotzky, R. F., & Burstein, D. 2003, ApJS, 145, 39
Nagashima, M., & Gouda, N. 2001, MNRAS, 325, L13
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1995, MNRAS, 275, 720
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Oemler, A., Jr., Dressler, A., & Butcher, H. R. 1997, ApJ, 474, 561
Okamoto, T. & Habe, A. 1999, ApJ, 516, 591
Okamoto, T., & Nagashima, M. 2001, ApJ, 547, 109
Okamoto, T., & Nagashima, M. 2003, ApJ, 587, 500
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A. J., Butcher, H., Ellis, R. S., & Oemler, A., Jr. 1999, ApJ, 518, 576
Ponman, T. J., Cannon, D. B., & Navarro, J. F. 1999, Nature, 397, 135
Postman, M., Lubin, L. M., & Oke, J. B. 2001, AJ, 122, 1125
Quilis, V., Moore, B., & Bower, R. 2000, Science, 288, 1617
Rakos, K. D., Odell, A. P., & Schombert, J. M. 1997, ApJ, 490, 194
Rakos, K. D., & Schombert, J. M. 1995, ApJ, 439, 47
Sakamoto, T., Chiba, M., & Beers, T. C. 2003, A&A, 397, 899

Schindler, S. 1999, A&A, 349, 435

Shen, S., Mo, H. J., White, S. D. M., Blanton, M. R., Kauffmann, G., Voges, W., Brinkmann, J., & Csabai, I. 2003, MNRAS, 343, 978

Smail, I., Edge, A. C., Ellis, R. S., & Blandford, R. D. 1998, MNRAS, 293, 124

Sofue, Y., Koda, J., Nakanishi, H., & Hidaka, M. 2003, PASJ, 55, 75

Sofue, Y., Tutui, Y., Honma, M., Tomita, A., Takamiya, T., Koda, J., & Takeda, Y. 1999, ApJ, 523, 136

Solanes, J. M., Manrique, A., García-Gómez, C., González-Casado, G., Giovanelli, R., & Haynes, M. P. 2001, ApJ, 548, 97

Spitzer, L., Jr. 1978, Physical Processes in the Interstellar Medium (New York; Wiley-Interscience)

Takeda, H., Nulsen, P. E. J., & Fabian, A. C. 1984, MNRAS, 208, 261

Takizawa, M., & Mineshige, S. 1998, ApJ, 499, 82

Toomre, A., & Toomre, J. 1972, ApJ, 178, 623

Tormen, G., Moscardini, L., & Yoshida, N. 2003, MNRAS submitted (astro-ph/0304375)

Treu, T., Ellis, R. S., Kneib, J. -P., Dressler, A., Smail, I., Czoske, O., Oemler, A., Jr, & Natarajan, P. 2003, ApJ, 591, 53

Valluri, M. 1993, ApJ, 408, 57

van Dokkum, P. G., Franx, M., Kelson, D. D., Illingworth, G. D., Fisher, D., & Fabricant, D. 1998, ApJ, 500, 714

Vollmer, B. 2003, A&A, 398, 525

Vollmer, B., Cayatte, V., Balkowski, C., & Duschl, W. J. 2001, ApJ, 561, 708

Vollmer, B., Marcelin, M., Amram, P., Balkowski, C., Cayatte, V., & Garrido, O. 2000, A&A, 364, 532

Yamada, M., & Fujita, Y. 2001, ApJ, 553, L145

Yano, T., Nagashima, M., & Gouda, N. 1996, ApJ, 466, 1

Yoshida, M., et al. 2003, AJ in press (astro-ph/0310044)